

SEARCH FOR TEMPORAL CHANGES IN SEISMIC VELOCITIES USING LARGE EXPLOSIONS
IN SOUTHERN CALIFORNIA*

Clarence R. Allen and Donald V. Helmberger
Seismological Laboratory
California Institute of Technology
Pasadena, California 91109

Abstract.--For many years, large explosions within the Caltech seismic network have occurred periodically at a quarry near Corona (75 km southeast of Pasadena) and at the Eagle Mountain iron mine (240 km east of Pasadena). Explosions have taken place almost daily since 1948 at Eagle Mountain. The long-established station at Hayfield, very close to the mine, permits accurate determinations of apparent velocities to distant stations such as Barrett, and this particular path crosses the epicentral region of the 1968 Borrego Mountain earthquake ($M = 6.4$). The first arrival at Barrett, at a distance of 172 km, is a refracted wave, but a distinct second arrival presumably represents a crustal phase. There has been no systematic change in the apparent P-wave velocity of either phase since 1962; maximum observed variation from the mean velocities is less than 2% for 32 events distributed throughout the 1962-1973 period. Fewer but larger events have taken place at Corona since 1949. Nine of these events at roughly three-year intervals were recorded throughout the network as well as onsite for timing purposes. The observed variation in P-wave velocity is less than 3-1/2% for all paths, and all variations can probably be explained by instrumental and reading inaccuracies. Because of the timing of events and their locations, the results from Eagle Mountain and Corona do not completely rule out dilatancy effects prior to the Borrego Mountain and San Fernando earthquakes -- the two major shocks of this period. But the observations do put certain restrictions on the possible size and nature of any proposed dilatancy regions, and there are no discernible systematic trends in the 24 years of data along any paths.

*California Institute of Technology, Division of Geological and Planetary Sciences, Contribution No. 2371.

Introduction.--In the search for possible seismic velocity changes precursory to earthquakes, man-made explosions have several advantages over natural earthquakes in establishing local velocities. In particular, (1) explosions may recur at the same localities over many years, especially when associated with mining or quarry operations, (2) the sources of explosions can be delineated considerably more accurately than most natural earthquakes, particularly with regard to depth, (3) opportunities exist for directly establishing the exact origin times for explosions, and (4) for large explosions, seismic arrivals at nearby stations are particularly impulsive and easy to read accurately.

For many years, large explosions within the Caltech seismic network have occurred at various mines and quarries throughout southern California. Many of these have long been used in establishing the local crustal structure (Wood and Richter, 1933; Gutenberg, 1951a, 1951b; Shor, 1955; Press, 1960.) The largest and most consistently detonated explosions have been at a rock quarry near Corona (75 km southeast of Pasadena) and at the Eagle Mountain iron mine (240 km east of Pasadena). This study is primarily concerned with P-wave arrivals from explosions at these two sources as recorded at various stations of the Caltech network, particularly during the time intervals including the 1968 Borrego Mountain earthquake ($M = 6.4$) and the 1971 San Fernando earthquake ($M = 6.4$). Our purpose has been to try to establish the presence or absence of local P-wave velocity changes prior to these events, as well as to look for possible long-term regional velocity changes that might be associated with even larger future events.

Eagle Mountain explosions.--Since iron mining operations started in 1948 at Eagle Mountain, California, explosions have taken place almost daily in the various mine pits. Almost every week has included at least one event large enough to be clearly recorded at seismic stations of the Caltech network across the Salton trough to the southwest. The station at Hayfield (HAY) was established in 1956 and is only 22 km southwest of the mine (Fig. 1). Almost in line with Eagle Mountain and Hayfield, but 150 km farther southwest, is the station at Barrett (BAR), which has operated since 1952. The apparent velocities of explosion-generated waves along this line are particularly interesting because of the fact that the 1968 Borrego Mountain earthquake ($M = 6.4$) occurred almost exactly midway between the two stations, and thus the opportunity exists for searching for possible precursory velocity changes. The data of Whitcomb *et al.* (1973) for the 1971 San Fernando earthquake -- of similar magnitude -- suggests that a lowering of the apparent velocity of P waves might be expected about 3-1/2 years prior to the time of the 1968 earthquake.

Explosions at the Eagle Mountain Mine have occurred in three principal pit areas, spread over a distance of about 8 km (Fig. 1). Until recently, it has not been possible to associate given explosions with specific pit sources. Fortunately, however, the alignment of pits is such that the

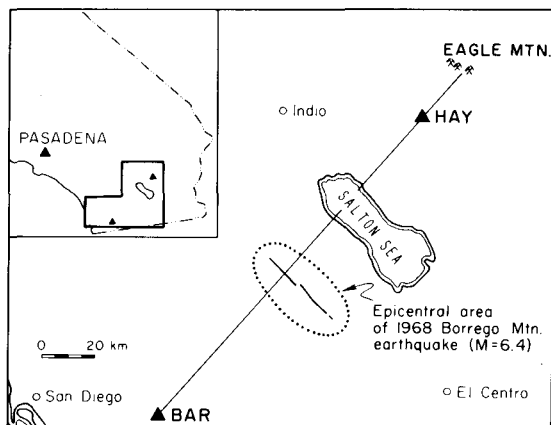


Figure 1.--Map showing locations of the Eagle Mountain explosions relative to the Caltech seismographic stations at Hayfield and Barrett, as well as to the epicentral area of the 1968 Borrego Mountain earthquake on the San Jacinto fault zone (surface breaks indicated).

Hayfield station is about equally distant from each, and the path to Barrett is approximately perpendicular to the line of pits. Thus the apparent velocities computed by using the BAR-HAY times are essentially independent of the particular pit source. Explosion yields have varied from day to day, the largest being in the order of 400,000 lbs of ammonium nitrate. In the first few months of 1973, several events exceeded an equivalent magnitude of 3.0, and events equivalent to magnitudes between 2.0 and 3.0 occurred several times each week.

First arrivals at Hayfield are, as might be expected, marked simply by disappearance of the trace on the seismogram. Very accurate reading is thus possible, although the primary limitation -- particularly in the early years -- is the time correction. In this study, only those events were used for which little extrapolation of clock rates was necessary. Most explosions occurred within two hours prior to 0000 GMT, and in almost every case, records were chosen on which the radio time signal could be read for that hour.

Barrett is 172 km from Eagle Mountain, and the first arrival there is clearly a refracted arrival. A stronger and very impulsive arrival about 1.6 sec later, however, presumably represents a crustal phase -- perhaps a Moho reflection. Both of these arrivals can generally be read with

considerable confidence, and the radio time signals and clock corrections here have historically been more satisfactory than at Hayfield.

Between 1962 and 1973, some 32 Eagle Mountain explosions have been timed at both Hayfield and Barrett, and the resulting travel-time differences are shown in Fig. 2. In many cases an attempt was made to measure two events occurring within a few days of one another, in order to

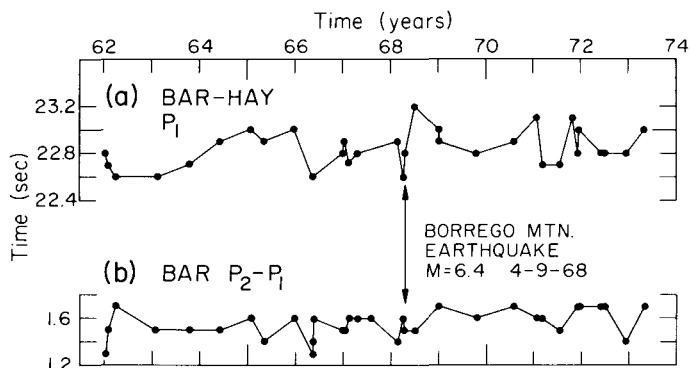


Figure 2.--(a) Travel-time differences of first-arriving P waves between Barrett and Hayfield for Eagle Mountain explosions between 1962 and 1973. (b) Travel-time differences between first and second P-wave arrivals at Barrett for most of the same events as those in (a).

get a feel for the accuracy of readings during an interval in which no velocity changes presumably took place. The average travel time between Hayfield and Barrett for these 32 events was 22.84 sec, with a standard deviation of 1.54 sec. The maximum variation from the average for any single reading was 1.6%. This travel time corresponds to an apparent velocity between the two stations of 6.55 km/sec.

No systematic changes or trends in the travel times are apparent to us on Fig. 2(a), and we conclude that all of the variation in individual times can be explained by reading and instrumental errors. It should be noted that each of the points in Fig. 2(a) represents the algebraic combination of six separate and independent readings on the seismograms: two arrival times, two clock corrections, and two measurements of the distances between relevant minute marks. The maximum spread of 0.6 sec in the 32 points appears to us to be a reasonable measurement error.

For most of the records on which first arrivals at Barrett and Hayfield were read, the time interval between the two arrivals at Barrett (P_1 and P_2) were also read. These are plotted in Fig. 2(b). The average is 1.55 sec, with a standard deviation of 0.12 sec. We again conclude that the variation can be explained solely by measurement errors. The apparent velocity between Hayfield and Barrett corresponding to the P_2 arrival is 6.13 km/sec.

In Fig. 3, the apparent velocity of the P_1 arrival is plotted on the same scale as that used by Whitcomb *et al.* (1973) in order that the size of variations might be compared. We conclude that these particular apparent velocities, as well as those of the P_2 arrivals (not plotted), do not show significant variations in the years prior to the 1968 Borrego Mountain earthquake comparable to those reported by Whitcomb *et al.* (1973) for the 1971 San Fernando earthquake.

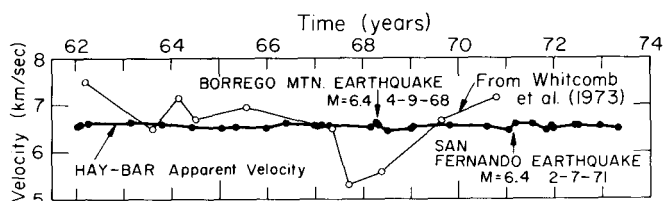


Figure 3.--Apparent velocities between Hayfield and Barrett (heavy line), derived from the data of Fig. 2. Lighter lines shows observations of Whitcomb *et al.* (1973) (for the San Fernando earthquake) in order to compare sizes of possible variations.

In comparing these data with those of the San Fernando earthquake, several points should be kept in mind:

(1) All of the arrivals used in the study of Whitcomb *et al.* (1973) were direct P arrivals, whereas the P_1 arrival in this study is clearly a refracted phase representing greater depth of penetration. Even our P_2 phase -- although probably a crustal phase -- presumably represents a relatively deep crustal penetration and is perhaps a Moho reflection from an area roughly beneath that of the Borrego Mountain earthquakes. Thus we can only state that significant velocity variations were not apparent at this depth, and it should be noted that the deepest shocks of the Borrego Mountain series were at about 12 km, with most of the activity at about 5 km (Hamilton, 1972; Allen and Nordquist, 1972).

(2) Although measuring apparent velocities between Pasadena and Riverside, Whitcomb *et al.* (1973) used as sources earthquakes within and

near the epicentral area of the subsequent San Fernando earthquake. All of the sources used in this study were explosions, and all took place far outside of the epicentral area of the Borrego Mountain earthquake. In a continuing study of the San Fernando earthquake, however, Anderson and Whitcomb (submitted for publication) claim that earthquakes outside the epicentral area also give rise to decreased velocities prior to the event, when recorded at stations on the opposite side of the epicentral area. Thus they feel that the velocity decrease is truly a path effect rather than a source effect.

(3) The San Fernando earthquake was clearly caused by thrust faulting, whereas the Borrego Mountain earthquake was associated with almost pure strike slip. Thus the strain build-up might be quite different in both nature and magnitude.

Corona explosions.--Another source of large controlled events occurring within the Caltech network is the Corona quarry (Fig. 4). The blasts produced by this source are rather infrequent but have been well recorded over a 24-year period, providing an opportunity to study possible long-term velocity variations that have been postulated preceding major

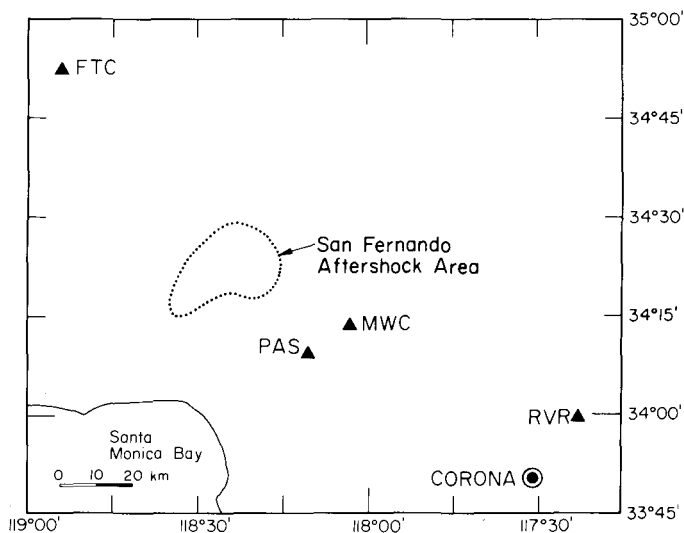


Figure 4.--Map showing locations of the Corona explosions relative to the Caltech seismographic stations, as well as the San Fernando aftershock area.

earthquakes. The site location as given in Fig. 4 has remained essentially the same since 1949. All the shots occurred along a constant longitude of $117^{\circ} 30.4'$ W with about a 1 km variation in latitude, centered at $33^{\circ} 50.8'$ N. The events were all timed at the source with a timing accuracy of about 0.1 sec. Another uncertainty of 0.1 sec is introduced to cover variation in ranges and positioning of the seismic sensor from the point of detonation. These blasts were all large, many greater than a million pounds of explosives, and are easily recorded at the most distant stations of the Caltech network. It is difficult to estimate the timing accuracy at the receivers due to clock errors, but we have assigned an error of 0.1 sec to instrumental inaccuracy and an additional .05 sec reading error. The largest estimated timing error a reading can have is thus 0.35 seconds. The data are presented in the Table. The scatter in the values appears to be well within this bound with the exception of Riverside, the readings in 1951 and 1967 occurring at the extremes. It appears that the first arrival at SBC is a Pn phase followed by a strong crustal arrival. Since Pn is small, it is sometimes overridden by the background noise, and in this situation the larger crustal phase becomes the apparent first arrival. The scatter of the SBC times gives a rough estimate of the effects of this type of misinterpretation.

Some of the average velocities computed from the Table are presented in Fig. 5. The points appear to be randomly scattered about the average, although many of the events appear anomalously low or high at all stations. This effect can be easily produced by origin time inaccuracy. The curves for PAS and MWC represent roughly the same profiles, and viewed together they do not indicate any obvious long-term trend.

A portion of our results relevant to the proposed San Fernando anomaly is given in Fig. 6. The apparent velocities from MWC and PAS to FTC are included for comparison with the observations of Whitcomb et al. (1973). The average velocity to FTC as well as the apparent velocity from PAS and MWC to FTC are somewhat lower than the normal velocity of 6.8 km/sec found by Whitcomb et al. (1973). Furthermore, it would appear that the average crustal velocity found in this region is quite low, 6.0 km/sec by Richter (1950), 6.2 km/sec by Shor (1955) and 6.1 km/sec by Press (1960). Using the monolith blasts discussed by Shor (1955) allows a rough reversed profile over the region. The results indicate an average velocity of 6.3 km/sec. However, there is evidence for a somewhat higher velocity along the PAS to RVR profile, the apparent velocity being 6.5 km/sec. There is also considerable evidence for a Conrad discontinuity as discussed by Shor (1955). These results suggest that the events used by Whitcomb et al. (1973) are relatively deep so that these high velocities can be obtained. The large variation in the velocities might then be explained in terms of source depth and the shift in cross-over distance. Our results do not rule out the proposed anomaly as indicated in Figure 6 but would require a rather rapid decrease in velocity just after the 1967 event.

Our results also suggest that the proposed anomaly must occur at considerable depth, near the base of the crust, to explain the high velocities obtained normally.

TABLE OF TRAVEL TIMES

	Aug 6 1949	Mar 27 1951	Apr 18 1956	Feb 18 1958	Oct 10 1964	July 18 1967	Oct 16 1969	Jan 8 1973	Ave.
RVR (20.3)	3.9	3.3	3.9	3.3	3.8	3.5	3.5	3.6	3.5
MWC (65.9)	11.5	11.4	11.1	11.1	11.3	11.0	11.0	11.4	11.2
PAS (70.0)	11.9	11.7	11.9	12.0	12.0	11.6	11.8	11.8	11.8
PLM (81.6)	13.7	13.4	13.8	13.4		13.4	13.2	13.4	13.5
FTC (170.9)			28.1	27.7	28.0	27.6	27.9		27.9
ISA (219.3)			34.2	33.6	34.0	33.9	33.9	32.9	33.7
BAR (150.9)			23.6	23.7	23.8	23.0	23.5	23.3	23.5
CLC (218.6)	33.8	33.5	34.0		34.0	33.4	33.3	33.7	33.7
SBC (214.1)	31.9 34.1			32.6		31.1 33.2		32.1 34.0	

Travel times in seconds between Corona and stations for the eight events. The distance to the various stations expressed in (km) is given below each station.

Conclusions.--The many explosions that have occurred at Corona and Eagle Mountain between 1949 and 1973 show travel times to stations of the Caltech network that have not varied outside of the limits of possible experimental error during this interval, which includes the times of both the major 1968 Borrego Mountain and 1971 San Fernando earthquakes. Because of the timing of the explosions and their locations, these results do not completely rule out the possibility of dilatancy effects that might have preceded these two events, such as that proposed by Whitcomb et al. (1973),

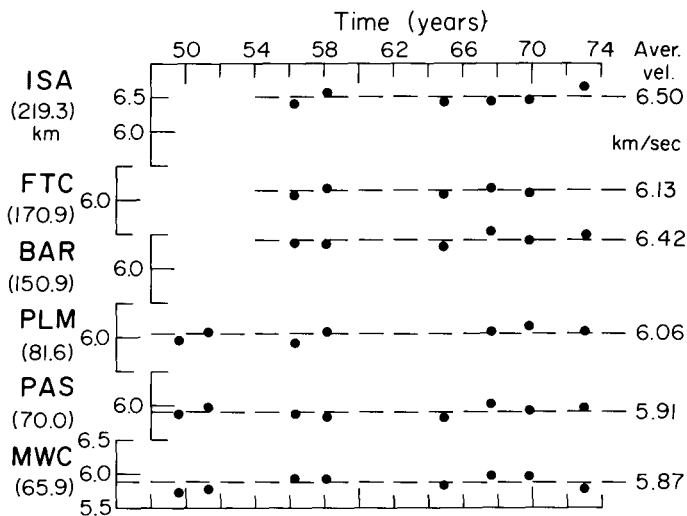


Figure 5.--Apparent velocities between Corona and various stations as derived from the data of travel time table.

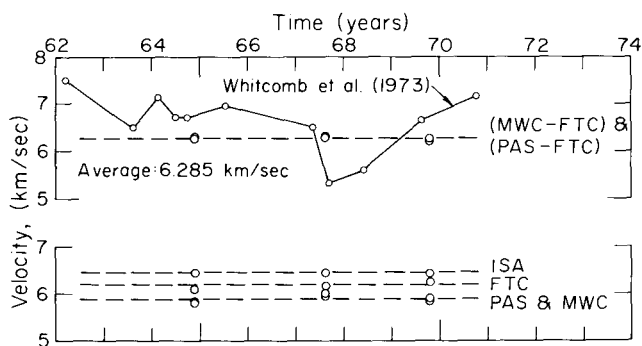


Figure 6.--Apparent velocities between (MWC-FTC) and (PAS-FTC) compared with the Whitcomb et al. anomaly. The average velocities between Corona and relevant stations are displayed in the lower plot.

but the results do put certain restrictions on the possible size and nature of any postulated dilatant regions. Furthermore, the fact that there have been no systematic changes in travel times along any of the paths during the 24-year interval suggests that there are no discernible long-term regional velocity changes that might be precursory to a future earthquake of significantly larger magnitude than those of 1968 and 1971.

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